Characterization of Scattered Radiation Profile in Volumetric 64 slice CT scanner: Monte Carlo Study Using GATE

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***Abstract*– It is commonly understood that scattered radiation in X-ray computed tomography (CT) reduces the CT number and degrades the quality of reconstructed images. This effect is more pronounced in multi detector CT scanners with extended detector aperture mostly using cone-beam configurations, which are much less immune to scatter than fan-beam and single-slice CT scanners. To perform accurate scatter correction, it is essential to characterize scattered radiation in Volumetric CT. As characterization of scattered radiation behavior using experimental measurement is a difficult and time consuming approach, Monte Carlo simulation can be an ideal method. In this study we used Geant4-based simulation package, GATE, to model x-ray photon interactions in the phantom and detector. The Monte Carlo simulation was validated through comparison with experimental measurement data. Thereafter, the effect of different parameters such as tube voltage and phantom material on the scatter profile and Scatter to Primary Ratio (SPR) was calculated. We also compared the simulated SPR curves with experimental data which was measured with array blocker method. The experimental technique assumed to be the gold standard technique. The comparison between simulation and experimental data in SPR showed error less than 5 %.**

The results indicate that the GATE Monte Carlo code is a useful tool for investigation of scattered radiation characterization in CT scanners. Moreover, there is a possibility of take advantage of GATE for simulation of PET and CT scanners in order to simultaneously asses the contribution of scattered radiation in PET/CT scanners.

I. INTRODUCTION

It is well known that contamination of CT data with scattered radiation reduces reconstructed CT numbers and introduces cupping artifacts [1, 2] in the reconstructed images. This effect is more pronounced in multi detector CT scanners with extended detector aperture mostly using cone-beam configurations, which are much less immune to scatter than fan-beam and single-slice CT scanners. In the context of CT imaging different groups have proposed methods for assessment of the scatter component including experimental measurements, mathematical modeling and Monte Carlo simulations for both fan- and cone-beam configurations. However, most published papers investigating the distribution of scattered radiation in the fan-beam geometry used either simple experimental measurements based on the use of a single blocker [3, 4, 5] or comprehensive Monte Carlo simulations [5, 6, 7]. Experimental measurement of scatter profile utilizing lead as a blocker of primary photons produces secondary scattered radiation which propagates remarkable errors in experimental measurements. Scattered photons originate from the lead blocker are attenuated through the phantom and finally reach the detector array and contaminate the scatter profile. It is possible to extract the scattered radiation profile induced from lead using experimental methods; however, it is impossible to appropriately model phantom attenuation of these photons. The issue of how to control and reduce scattered radiation in cone-beam CT remains a big challenge. Monte Carlo modeling is by far the most accurate and robust approach to calculate the scattered radiation. The GEANT4-based Monte Carlo simulation package GATE has been successful in the application of PET and SPECT with its precise modeling of various physics processes.

The aim of this study is to first validate the GATE Monte Carlo simulations for accurate modeling of volumetric 64 slice CT scanner. The validated GATE simulation package was then

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used to characterize the scatter to primary ratio for a range of x-ray energy spectra, varying isocenter to detector distances, and various phantom size and density. Simulation conducted to investigate scatter from a realistic, in order to determine the characteristics of various scatter components which cannot be separated in measurements.

II. MATERIAL AND METHOD

A. Volumetric 64 slice CT System

The simulated CT scanner in this study was GE LightSpeed VCT64-slice cardiac CT scanner (GE Healthcare Technologies, Waukesha, WI). This third generation CT scanner has 540 mm source to isocenter and 950 mm source to detector distance, 58,368 individual elements arranged in 64 rows of 0.625 mm thickness at isocenter, each containing 888 active patient elements and 24 reference elements with Highlight ($Y_2Gd_2O_3:Eu$) ceramic scintillator. The scanner is equipped with the Performix Pro Anode Grounded Metal-Ceramic Tube Unit which uses 56 degree fan angle, 7 degree target angle and minimum inherent filtration of 3.25 mm Al and 0.1 mm Cu at 140 kVp.

B. Phantoms

Two cylindrical phantoms were used for simulation and experimental measurments. The small phantom was water phantom with a wall made of Perspex material. The external diameter of this phantom is 215 mm and its wall thickness is equal to 6 mm. The large utilized phantom was polypropylene phantom. This phantom that normally used for modeling of bony structures has 350 mm diameter, suitable for large scan field of views.

C. Monte Carlo Simulation

The GATE (GEANT4 application for tomographic emission) Monte Carlo simulation package [9] is used to generate photons of varying energies and simulate their transport within different materials. GEANT4 provides three models for photon interactions: Standard, low Energy, and PENELOPE, which are all relevant in modeling x-ray medical imaging applications. The more accurate low energy electromagnetic model was chosen for use in the Monte Carlo simulation studies described here. In the GATE simulation of x-ray photons, every interaction process including the Compton and Rayleigh scatterings was labeled and the number of times that a photon undergoes the Compton or Rayleigh scatterings within the phantom or detector was counted, providing a means to separate the single or multiple incoherent or coherent scatterings. The simulated phantom was the same size, shape, and composition as the physical phantom used in the experimental measurements. To model x-ray tube emission with, simulated photons were emitted isotropically from a point source within a fan angle of 56° and cone angle of 4° so as to expose the entire phantom. The emitted photons can traverse the phantom and reach the 3 mm thick scintillator plate if they do not stop within the phantom by undergoing a photoelectric interaction. Production and transport of scintillation light in the crystal were not modeled. The photons deposited in the detector were recorded and separated by primary (defined as those that did not undergo any scattering within the phantom) and scatter (defined as those encountering at least one Compton or Rayleigh scattering in the phantom). All deposited energies of the primary or the scatter photons were then summed into $1\times1\times3$ mm^3 voxels to form corresponding images. Since we did not model the production and collection of scintillation light in the detector, a scaling applied to the simulated images necessary in order to relatively compare the simulated and measured images. The final primary and scatter images for a given x-ray kVp setting were obtained by summing the individual data generated at each energy according to the desired x-ray spectrum. Figure 1 shows the LightSpeed CT scanner that accurately modeled in GATE based on the specification provided by factory.

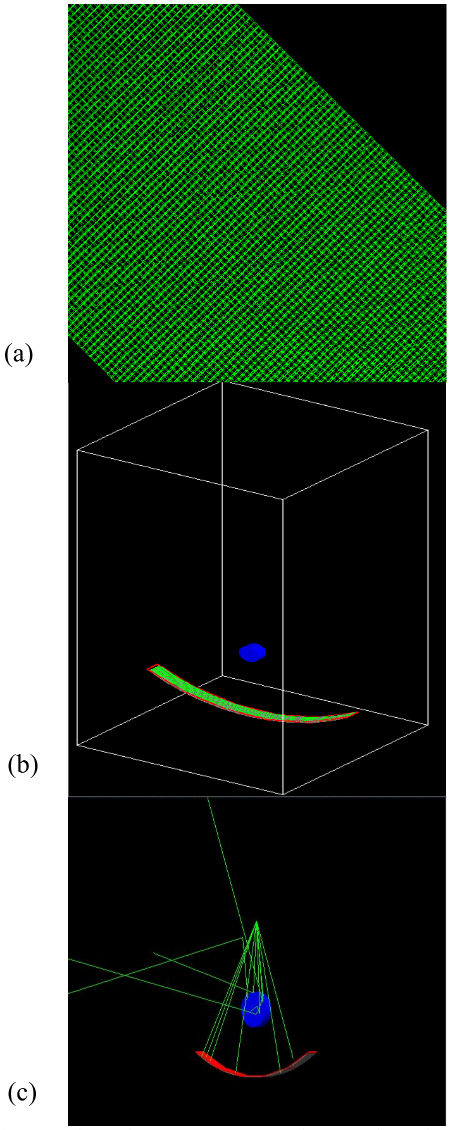


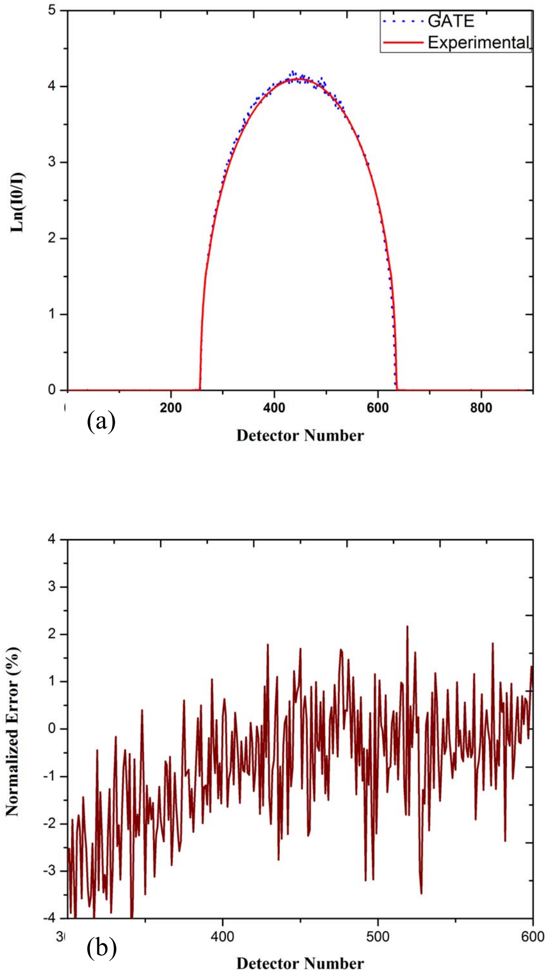
Fig. 1 (a) Top view of scanner's 64 rows detector (b) and (c) Geometry of simulated CT by GATE

III. RESULTS

Figure 2 shows simulated and experimental measurement of attenuation profiles at 140 kVp spectrum and normalized error between experimental and simulation data. In order to know how accurate our simulation is, the resulting simulated attenuation profile was compared with experimental attenuation profile. The method of comparison was based on normalized error (NE) which calculates the relative difference between simulation and measurement data. This method has been used as a figure of merit to evaluate differences between two data sets [8].

$$NE(u,v) = \frac{\mathrm{PMeasured(u, v) - PSimulation(u, v)}}{\mathrm{PMeasured(u, v)}}$$

Where u and v are detector element's coordinates, $P_{Measured}$ (u, v) and $P_{Simulation}$ (u, v) are the measured and simulated projection data for each detector element. The maximum relative difference between experimental and simulated data (in the region of phantom shadow) was close to 4%.



(a)

(b)

Fig. 2. (a) Comparison of attenuation profiles for a uniform cylindrical water phantom using experimental measurements (solid line) and GATE simulations (dash dot line) (b) Normalized error between measurements and GATE simulations.

Figure 3 shows the normalized scatter profile calculated from detector row 32 (the central row) using simulation at different x-ray tube voltages. It should be noted that scatter profile normalized to unit area of scatter in 140 kVp.

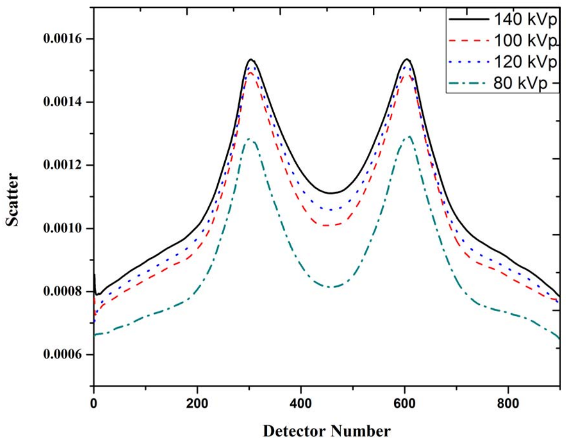


Fig. 3. Scattered radiation profile for cylindrical water phantom, at different tube voltages. The curves profile normalized to unit area of scatter in 140 kVp.

Figure 4 shows the normalized scatter profile at different tube voltages for the cylindrical Polypropylene phantom.

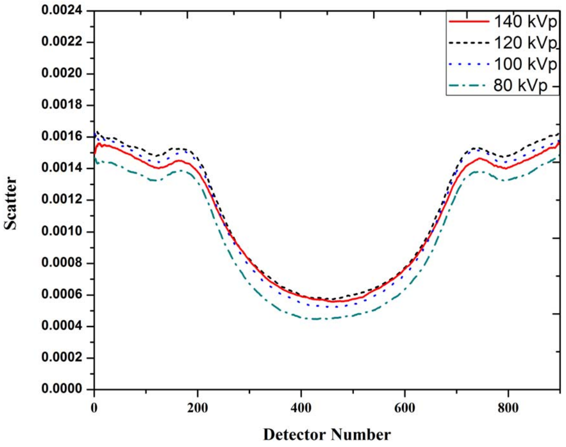


Fig. 4. Scattered radiation profile for cylindrical Polypropylene phantom at different tube voltages. Scatter profile normalized to unit area of scatter in 140 kVp.

Tube voltage dependence of the SPR was studied by calculating scatter to primary ratios for different x-ray kVp settings. In this part of simulation, the x-ray energy setting was changed from 80 to 140 with interval of 20 kVp for both water and polypropylene phantoms. We plot simulated SPR at the center of the phantom where the maximum value was achieved as a function of x-ray spectrum in Figure 5 and 6 for different phantom.

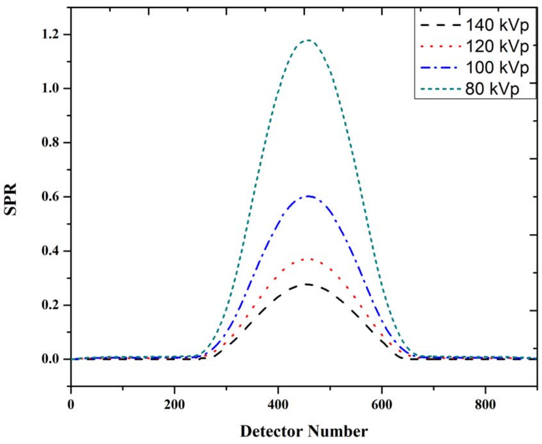


Fig. 5. Simulated SPR profile for cylindrical water phantom, at different tube voltage.

The Polypropylene phantom was used in order to mimic clinical conditions for obese patients.

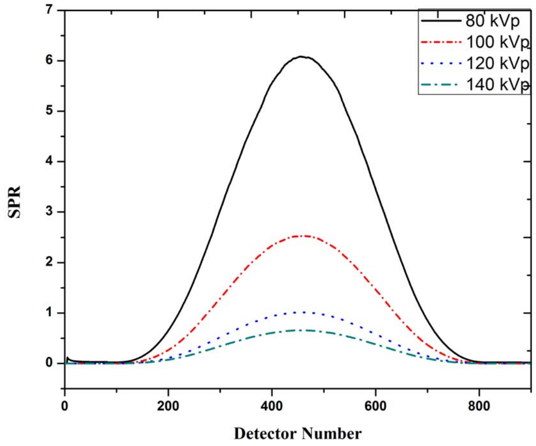


Fig. 6. SPR profile for cylindrical polypropylene phantom, at different tube voltage.

Figure 7 and 8 shows the comparison of experimental and simulation data in 140 kVp for water and polypropylene phantom. Experimental data was calculated using array blocker method [10].

Table I shows Average normalized error between experimental and simulation profile in different tube voltage and phantom.

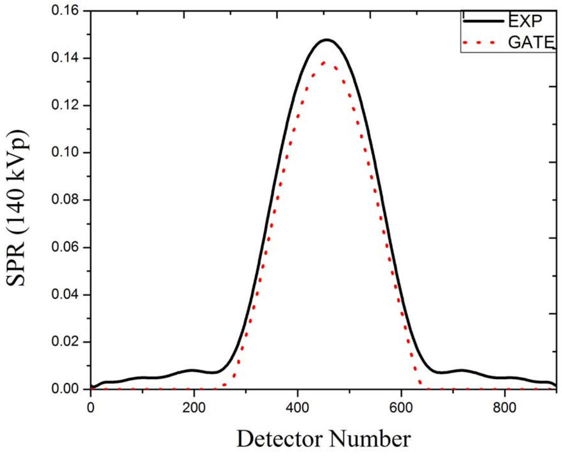


Fig. 7. Comparison of SPR curves in 140 kVp for water phantom.

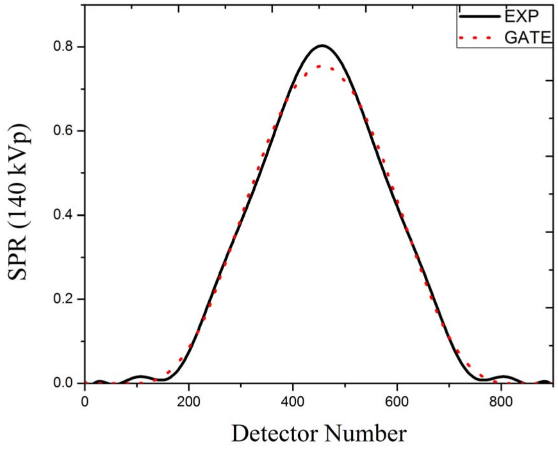


Fig. 8. Comparison of SPR curves in 140 kVp for polypropylene phantom.

TABLE I. AVERAGE NORMALIZED ERROR BETWEEN EXPERIMENTAL AND SIMULATION DATA IN DIFFERENT TUBE VOLTAGE AND PHANTOM

kVp	Phantom	
	Water	Polypropylene
80	5.1%	4.5%
100	3.7%	3.9%
120	2.7%	3.3%
140	2.2%	1.0%

IV. DISCUSSION

The Monte Carlo simulation is a suitable method for assessment of x-ray scatter magnitude and spatial distribution. Monte Carlo calculations offer the possibility of estimating physical parameters including x-ray scatter that are difficult or even impossible to calculate using experimental measurements.

The two peaks observed in the scatter profile in figures 3 and 4 are due to the trade-off between increasing the probability of Compton scattering while decreasing the transmission probability of scattered photons with increasing the attenuation length. It should be emphasized that the lower scattered photons in the center of the scatter profile covered by the phantom whose diameter is large compared to the mean free path of photons is the result of either absorption of incoming photons before undergoing a Compton event or attenuation of scattered photons after Compton scattering.

The higher SPR value in 80 kVp in figures 5 and 6 is due to the fact that transmitted primary radiation increases by increasing tube voltage. On the other hand, it is well known that the probability of compton scattering increases with increasing tube voltage (Figure 2 and 3). As a matter of fact, the amount of primary photons increases much more than the amount of scattered photons by increasing tube voltage. Therefore, the SPR decreases with increasing tube voltage.

V. CONCLUSION

In conclusion, scatter in Volumetric 64 slice CT was investigated by GATE Monte Carlo simulation package. The Monte Carlo simulation was validated through comparison with experimental measurement data. The validated GATE Monte Carlo simulation used to characterize the accurate scatter and SPR profiles in different x-ray kVp settings and air gaps as well as for different phantom sizes and densities. Accurate estimation of scatter and SPR will allow one to develop a more effective and precise scatter correction method in CT image reconstruction.

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